Quantitative analysis of inner-ear barotrauma using a Eustachian tube function analyzer

Naoharu Kitajima, Akemi Sugita-Kitajima and Seiji Kitajima

Abstract

(Kitajima N, Sugita-Kitajima A, Kitajima S. Quantitative analysis of inner ear barotrauma using a Eustachian tube function analyzer. *Diving and Hyperbaric Medicine*. 2016 June;46(2):76-81.)

Objectives: We investigated the relationship between Eustachian tube function and incidence of inner-ear barotrauma (IEBt) in recreational divers.

Methods: Sixteen patients who experienced a scuba diving injury affecting the inner ear and 20 healthy volunteers who had not experienced a diving injury participated. Healthy volunteers and divers with IEBt received impedance tests regularly to assess Eustachian tube function. Test results from these groups were compared.

Results: There were no significant differences between test results of IEBt divers and healthy volunteers. However, seven IEBt divers were judged to have irregular compliance curves on impedance testing. Seven of the 16 IEBt divers experienced vertigo. In nearly all of the IEBt divers with vertigo, hearing loss type was manifested as high-tone deafness, and IEBt symptoms appeared during diving. These symptoms were more serious especially when the diving depth was deeper.

Conclusions: To prevent IEBt in scuba divers, we recommend a thorough Eustachian tube function evaluation. Any dysfunction should be treated before engaging in scuba diving. We need to assess more divers who have experienced IEBt and thoroughly examine how their injury happened.

Key words

ENT; scuba diving; injuries; vertigo; patient monitoring; equipment

Introduction

The most common injuries in diving are middle ear and nasal sinus barotrauma.[1] Inner ear barotrauma (IEBt), which is related to pressure changes in the middle and inner ear, is less common after diving incidents, but can produce permanent and disabling injury to the vestibulocochlear system.[2] For example, IEBt during descent is directly related to impaired ability to equalize middle ear pressure on the affected side. Subsequently, sudden large pressure changes in the middle ear can be transmitted to the inner ear, resulting in damage to the vestibulocochlear system. The affected diver reports deafness and vertigo, singly or in combination.

In the present study, we investigated the relationship between Eustachian tube function and the incidence of IEBt in recreational scuba divers. We evaluated IEBt using impedance testing. Impedance testing mainly evaluates changes in air content within the middle ear during the Valsalva manoeuvre and swallowing. Thus, we reasoned that impedance testing would be an ideal method for examining ‘ear clearing’ in divers. In Japan, impedance testing is the most commonly used test for evaluating Eustachian tube function; sonotubometry,[3] tubotympanoaero-dynamography,[4] and nine-step inflation/deflation testing[5] are also used. To our knowledge, this is the first study to use impedance testing to evaluate IEBt in scuba divers.

Materials and methods

Sixteen patients who had experienced a scuba diving injury affecting the inner ear (eight men and eight women; mean age ± SD: 43.5 ± 12.4 years) and 20 healthy volunteers who had not experienced a diving injury (six men and 14 women; mean age ± SD: 33.5 ± 13.9 years) participated. This study was conducted in accordance with the Declaration of Helsinki for the ethical treatment of human subjects. All procedures were approved by the review board of Tokyo Medical University (No. 3032) and carried out with the adequate understanding of the subjects and their written consent. We used the diagnostic criteria of Edmonds et al.[6] to diagnose IEBt; that is, the presence of otological barotrauma, sensorineural or combined hearing loss, or tinnitus or demonstrable vestibular damage implying IEBt. In a previous study, we classified patients with scuba diving-related aural barotrauma into unilateral and bilateral groups.[7] In the present study, we examined the unilateral group with IEBt.

During the patients’ first visit to our clinic, the divers underwent nystagmic examinations at their bed side and audiometric measurements, including pure tone audiometry (PTA), tympanometry, Eustachian tube function testing and a fistula test. Based on the criteria for evaluating hearing, as determined by the Research Committee on Acute Profound Deafness, Ministry of Health and Welfare, Japan,[8] we calculated the average hearing level at five frequencies (0.25, 0.5, 1.0, 2.0, and 4.0 kHz), representing the worst PTA results. To evaluate hearing level, we tested air conduction. However, if there was a difference between air conduction and bone conduction (i.e., an air-bone gap), we used bone conduction testing instead.

A JK-05 Eustachian tube function analyzer (RION, Japan)

Figure 1
Examples of normal impedance test curves constructed from a healthy volunteer; opening pressures less than 200 daPa are consistent with a diagnosis of patulous Eustachian tube type, whereas opening pressures greater than 650 daPa are consistent with a diagnosis of stenotic Eustachian tube type

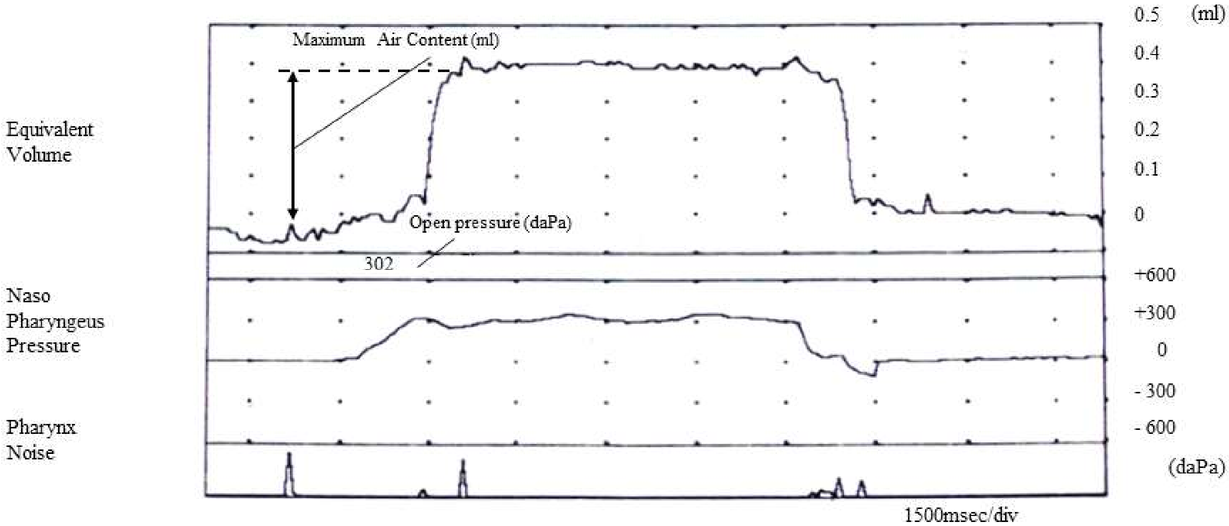
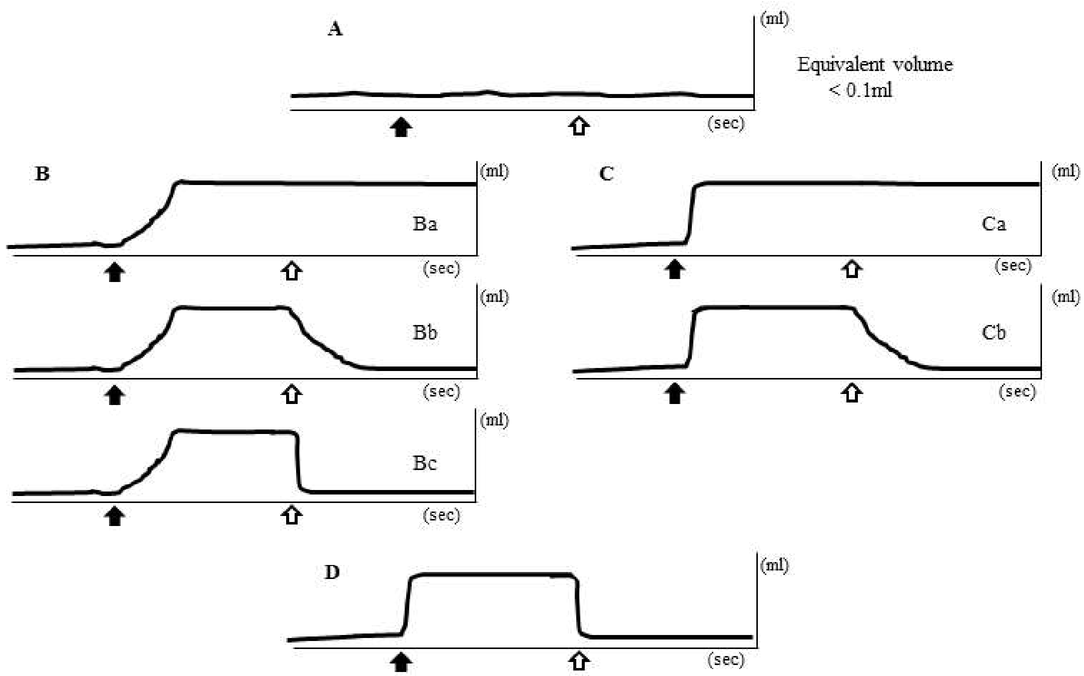


Figure 2
Classification of Eustachian tube function based on compliance curves; in each graph, the filled arrow at the lower left represents the start of the Valsalva manoeuvre, and the open arrow at the lower right represents swallowing after the Valsalva



was used to perform impedance testing. Examples of impedance test curves measured from a normal subject are shown in Figure 1. Impedance tests were performed by simultaneously recording tympanic membrane impedance and nasopharyngeal pressure. The passive opening capacity of the Eustachian tube during the Valsalva manoeuvre can be determined from the curve pattern of impedance changes recorded from the external ear canal.[9] The presence of respiratory fluctuations and opening pressures of less than 200 daPa are consistent with a diagnosis of patulous Eustachian tube, whereas opening pressures greater than 650 daPa are consistent with a diagnosis of stenotic

Table 1
Eustachian tube function results of healthy divers; * data not obtainable

Subject	Impedance Test				Eustachian tube function
	Opening pressure (daPa)	Maximum air content (ml)	Compliance curve	Respiratory fluctuation	
1	496	0.35	D	No	Normal
2	330	0.2	D	No	Normal
3	*	0.2	D	No	Normal
4	796	0.2	Cb	No	Stenotic
5	330	0.4	Cb	No	Stenotic
6	*	0.9	D	No	Normal
7	*	0.9	Cb	No	Stenotic
8	185	0.3	D	No	Normal
9	145	0.8	D	No	Normal
10	*	0.45	Cb	No	Stenotic
11	242	0.2	D	No	Normal
12	335	0.6	Cb	No	Stenotic
13	*	0.2	D	No	Normal
14	420	0.4	Cb	No	Stenotic
15	597	0.3	D	No	Normal
16	338	0.5	D	No	Normal
17	169	0.8	D	No	Normal
18	582	0.7	D	No	Normal
19	407	0.4	D	No	Normal
20	*	0.3	Cb	No	Stenotic

Eustachian tube type.[7] We defined the maximum value of equivalent volume as maximum air content in the middle ear. If we could not accurately determine the opening pressure because of a technical error, we diagnosed the patient with either stenotic or patulous Eustachian tube type from the shape of his or her compliance curve.

Classification of Eustachian tube function based on compliance curves is shown in Figure 2.[10] In each curve, the black arrow at the lower left represents the start of the Valsalva manoeuvre and the white arrow at the lower right represents swallowing after the Valsalva. When the Eustachian tube did not open or close for more than 10 seconds, we designated the compliance curve as type A or a, respectively. If the Eustachian tube opened or closed immediately, we designated the curve as type C or c, respectively. If Eustachian tube opening or closing was delayed, we designated the curve as type B or b, respectively. Compliance curves showing normal patterns were designated as type D, whereas those showing abnormal patterns were designated as 'other types' (A; Ba, Bb, Bc; and Ca, Cb; see Figure 2). If compliance curves had abnormal patterns, we designated the curves as 'stenotic' Eustachian tube type and diagnosed the patient with tubal stenosis. However, if respiratory fluctuations were evident from inspections of the compliance curves, we designated the curves as 'patulous' and diagnosed the patient with patulous Eustachian tube. If the Eustachian tube slightly opened (maximum air content < 0.1 ml), we designated the curve as type A for convenience and assigned the data point for maximum air content to 0.1 ml.

We compared Eustachian tube function in healthy volunteers with that in divers who experienced IEBt. Calculations were performed with Stat Mate 3 software (Atoms, Japan). Data are presented as means ± standard deviation. The Mann-Whitney U test was used for statistical analysis; $P < 0.05$ was considered significant.

Results

DIVERS WITHOUT IEBt

Seven of the 20 healthy volunteers were diagnosed with Eustachian tube dysfunction of the stenotic type (Table 1). With the impedance test, the mean ± SD opening pressure was 384 ± 184 daPa, and the maximum air content was 0.5 ± 0.2 ml. Seven of 20 healthy volunteers had irregular, type Cb compliance curves.

DIVERS WITH IEBt

There were no significant differences between the IEBt divers and healthy volunteers in terms of age. Twelve of the divers with otological symptoms were diagnosed with Eustachian tube dysfunction of the stenotic type (Table 2). For the impedance test, the opening pressure was 579 ± 341 daPa, and the maximum air content was

Table 2

Clinical findings of divers with inner-ear barotrauma; † parameters were technically difficult to measure; * maximum equivalent volume in A type was set to 0.1 ml for convenience

No.	Onset	Pure tone audiometry		Tympanometry	Impedance test				Eustachian tube function	Vertigo	Fistula sign
		dB (mean)	hearing loss type		Open pressure (daPa)	Maximum air content (ml)	Compliance curve	Respiratory fluctuation			
1	after ascent	16	dip (4,000Hz)	A	286	0.7	D	No	normal	No	No
2	not clear	19	flat or horizontal	A	1200	0.2	D	No	Stenotic	No	No
3	after ascent	19	dip (4,000Hz)	A	530	0.7	D	No	Stenotic	No	No
4	during descent	21	flat or horizontal	A	577	0.3	Bb	No	Stenotic	No	No
5	during ascent	22	high tone (gradual)	A	311	0.5	D	No	Stenotic	No	No
6	after ascent	25	middle tone	A	1200	0.2	Bb	No	Stenotic	No	No
7	after ascent	26	flat or horizontal	A	139	0.5	D	No	normal	No	No
8	during descent	26	middle tone	C1	611	0.4	D	No	normal	No	No
9	after ascent	33	high tone (gradual)	A	†	0.4	Ca	No	Stenotic	No	No
10	during diving (>10m)	9	high tone (abrupt)	A	503	0.4	Cb	No	Stenotic	Yes	No
11	during diving (>10m)	25	high tone (gradual)	A	614	0.6	D	No	normal	Yes	No
12	after ascent	25	low tone deafness	A	310	2.0	Bc	No	Stenotic	Yes	No
13	after ascent	26	high tone (abrupt)	A	370	0.7	Ca	No	Stenotic	Yes	No
14	during diving (>10m)	30	high tone (gradual)	A		0.1*	A	No	Stenotic	Yes	No
15	during diving (>20m)	41	high tone (gradual)	A	†	0.6	Ba	No	Stenotic	Yes	No
16	during diving (>20m)	106	flat or horizontal	C1		0.1*	A	No	Stenotic	Yes	Yes

0.5 ± 0.5 ml. There were no significant differences between IEBt divers and healthy volunteers on these variables. Seven divers were judged to have irregular compliance curves. Seven divers experienced vertigo and of these, six had irregular compliance curves (Table 2).

The clinical findings of IEBt divers are also summarized in Table 2. Except in the case of two IEBt divers (nos. 8 and 16; Table 2), tympanometry results of the IEBt divers were normal (Jerger A type). Five of the seven IEBt divers with vertigo experienced a high-tone hearing loss and IEBt symptoms during diving. The deeper the diving depth, the more serious were the symptoms. Of the IEBt divers who underwent fistula testing, only one diver (No. 16) tested positively. This diver was subsequently diagnosed with perilymphatic fistula after exploratory tympanotomy, during which both the oval and round windows were patched with fascia.

Discussion

Generally, IEBt among scuba divers is believed to be caused by any one of three conditions: a haemorrhage in the inner ear, a tear of the labyrinthine membrane, or a perilymphatic fistula,[11] moreover it is thought to be caused by a pressure difference between the inner ear and the middle ear cavity. The general characteristics described for IEBt are:

- the same symptoms are experienced repeatedly with pressure load;
- hearing loss, tinnitus, or both;
- unilateral hearing loss;
- primarily high-tone deafness (gradual/abrupt form and flat or horizontal form);
- hearing ability is moderately impaired;
- satisfactory convalescence.[12]

For the most part, our present findings are comparable to these criteria.

In the present study, most of the IEBt divers had Eustachian tube dysfunction (Table 2). The IEBt divers with irregular compliance curves on impedance testing tended to experience vertigo (Table 2). We previously reported that to avoid a diving injury, it is particularly important to have an improved compliance curve.[10] These results are in line with our hypothesis.

In the present study, five of the seven IEBt divers with vertigo displayed type a/b (including type A) compliance curves when subjected to impedance testing (Table 2). This means that divers with type a/b compliance curves are prone to vertigo during diving, probably because expanding air in the middle ear is not released promptly via the Eustachian tube. However, seven of the healthy volunteers had irregular compliance curves of the Cb type (Table 1), indicating that IEBt does not always occur in divers displaying type Cb compliance curves. The Eustachian tubes of divers with type Cb compliance curves opened easily only if the divers ascended from a dive slowly. In this case, the diver could release expanding air volume from their Eustachian tubes without difficulty. In general then, type Cb compliance curves might be considered to be a normal type of curve, as can type D curves. Needless to say, whether a diver with a type Cb curve is able to clear his Eustachian tubes successfully depends on his diving skills and experience.

IEBt onset does not always depend on diving depth.[13,14] However, in our study, when the dive was deeper, IEBt divers were more likely to experience vertigo. Excessive pressure caused by forceful Valsalva manoeuvres could be one contributory factor. The opening pressures of the IEBt divers were not always higher than those of the healthy volunteers. However, divers who had difficulty clearing their ears may have become impatient due to discomfort, leading them to Valsalva more forcefully.

In the diver with a perilymphatic fistula (No. 16), both inner-ear dysfunction and Eustachian tube dysfunction were more serious than those in other divers with IEBt. Therefore, we need to be particularly aware about perilymphatic fistula being the most serious cause of IEBt. In certain cases, it is difficult to diagnose whether divers with IEBt will develop perilymphatic fistula. Thus, in these cases, fistula testing and high-resolution CT scanning of the temporal bone[15] need to be performed. If possible, levels of cochlin tomo-protein (CTP), a perilymph-specific protein,[16] should also be measured.

Conclusions

This study supports the idea that divers who experience IEBt should undergo thorough evaluation of their Eustachian tube function and of their vestibulocochlear system if they are to receive proper treatment. To ensure safe diving that avoids inner-ear-associated injury, divers first need to determine whether they are prone to IEBt. To dive safely, they would need to display normal (type D or Cb) compliance curves. To lessen the likelihood of injury, divers should also be instructed on how to solve diving-related problems. Since various other factors make it difficult to evaluate divers thoroughly, we need to assess more divers who have experienced IEBt and thoroughly examine how their injuries happened.

References

1 Strutz J. Otorhinolaryngologic aspects of diving sports. *HNO*. 1993;41:401-11.

2 Klingmann C, Wallner F. Health aspects of diving in ENT medicine. Part I: diving associated diseases. *HNO*. 2004;52:757-67.

3 Virtanen H. Sonotubometry. An acoustical method for objective measurement of auditory tubal opening. *Acta Otolaryngol*. 1978;86:93-103.

4 Iwano T, Kinoshita T, Hamada E, Ushio K, Yamashita T, Kumazawa T. Sensation of ear fullness caused by Eustachian tube dysfunctions. *Auris Nasus Larynx*. 1991;18:343-9.
5 Uzen C, Adali MK, Tas A, Koten M, Karasalihoglu AR, Devren M. Use of the nine-step unflation/deflation test as a predictor of middle ear barotrauma in sports scuba divers. *Br J Audiol*. 2000;34:153-63.
6 Edmonds C. Ear Barotrauma. In: Edmonds C, Lowry C, Pennefather J, Walker R, editors. *Diving and subaquatic medicine*, 4th ed. Boca Raton FL: CRC Press; 2005. p. 73-91.
7 Kitajima N, Kitajima-Sugita A, Kitajima S. [A study of the Eustachian tube function in patients with a scuba diving accident.] *Nippon Jibiinkoka Gakkai Kaiho (Tokyo)*. 2012;115:1029-36. Japanese.
8 Nomura Y. Summary, [The Research Committee on Acute Profound Deafness.] Ministry of Health and Welfare, Japan. 1985. p. 1-3. Japanese.
9 Kumazawa T, Iwano T, Ushiro K, Kinoshita T, Hamada E, Kaneko A. Eustachian tube function tests and their diagnostic potential in normal and diseased ears. *Acta Otolaryngol (Stock)*. 1993;113(Suppl 500):10-13.
10 Kitajima N, Sugita-Kitajima A, Kitajima S. [Criteria for resuming SCUBA diving for divers who experience a diving accident.] *J J Aerospace Env Med*. 2013;50:37-44. Japanese.
11 Parell GJ, Becker GD. Conservative management of inner ear barotrauma resulting from scuba diving. *Otolaryngol Head Neck Surg*. 1985;93:393-7.
12 Yanagita N. Inner ear barotrauma –[Clinical and experimental studies- *Pract Otol (Kyoto)*.] 1986(Suppl 3):20-32. Japanese.
13 Schuknecht HF, Gacek RR. Surgery on only-hearing ears. *Trans Am Acad Opthalmol Otolaryngol*. 1973;77:257-66.
14 Harker LA. Experimental rupture of the round window membrane. *Trans Am Acad Opthalmol Otolaryngol*. 1974;78:448-52.
15 Shupak A. Recurrent diving-related inner ear barotrauma. *Otol Neurotol*. 2006;27:1193-6.
16 Ikezono T, Omori A, Ichinose S, Pawankara R, Watanabe A, Yagi T. Identification of the protein product of the Coch gene-hereditary deafness genes the major component of bovine inner ear protein. *Biochim Biophys Acta*. 2001;3:258-65.

Conflict of interest: nil

Submitted: 20 November 2015; revised 08 February and 19 March 2016
Accepted: 23 April 2016

Naoharu Kitajima[1,2], Akemi Sugita-Kitajima[1,3], Seiji Kitajima[1]

[1] Kitajima ENT Clinic, Tokyo, Japan
[2] Department of Otolaryngology, Tokyo Medical University, Tokyo, Japan
[3] Department of Otolaryngology, St. Marianna University School of Medicine, Kanagawa, Japan

Address for correspondence:
Naoharu Kitajima
Kitajima ENT Clinic
1-15-15 Tagara Nerima-ku
Tokyo 179-0073, Japan
Phone: *+81-(03)-3930-4830*
E-mail: *<nao-ake@bk2.so-net.ne.jp>*